

## DEVELOPMENT OF A MODEL 4 TESLA DIPOLE MAGNET

M.Kumada, T.Fujisawa, Y.Hirao, NIRS, Chiba, Japan

M.Endo, M.Aoki, T.Kohda, Sumitomo Special Metal Co., Ltd., Osaka, Japan

Y.Iwashita, NSRF, ICR, Kyoto, Japan

I.Bolshakova, R.Holyaka, MSL, Lviv, Ukraine

### Abstract

In order to respond to a need of reduction in size of a medical accelerator, a new idea has to be developed. A model permanent magnet exceeding 4 Tesla was recently designed, manufactured and measured. In the past, this field level was only achievable by a superconducting magnet or a pulsed high current coil magnet. In order to exceed a field level of an inherent property of a material of a dipole magnet, a new technique is invented. Although the size of a magnet gap is small in a model, reasonable size magnet can be constructed by a linear scaling. The high field DC magnet can be used in a cyclic accelerator either in cyclotron or in FFAG (Fixed Field Alternating Gradient) Accelerator.

### 1 INTRODCUTON

Permanent magnet (PM) has been applied in an accelerator field mostly as undulator/wiggler in synchrotron radiation storage ring. There is a myth about PM. They are: The field strength is weak compared to electro-magnet or superconducting magnet. Even when residual field strength  $B_r$ , magnet material itself is high, working point of material in most of the cases is at half of a residual field  $B_r$ . PM is only good at small aperture magnet like undulator/wiggler. A high  $B_r$  material is expensive. PM is unstable as magnetization strength depends upon temperature at a level of a few parts in thousand. Variation of strength of magnetization is as much as a few percent and a high homogeneity required from accelerator performance is difficult, etc.

However, recently at Fermilab, a large quantity of ferrite magnet was developed and applied to an 8 GeV antiproton storage ring [1]. The residual field  $B_r$  of the ferrite is 1/3 of  $N_d B_c$  magnet. They made a remarkable progress in PM technology. They have solved temperature stability problem and homogeneity problem. The field strength of the Recycler PM is only 1.5 kG or so, which is about 1/3 of a ferrite material's  $B_r$ .

The strong PM magnet is challenged for quadrupole magnet. The 250 T/m magnets were the strongest for the quadrupole [2]. For the wiggler magnet, 3 Tesla Permanent magnets is so far the strongest [3]. The structure of this PM is the one proposed by K.Halbach where a combination of iron and PM magnet is placed periodically in a linear direction. This configuration can be extended to a circular type dipole magnet. We found out that when the iron pole is driven into a saturated level,

the field strength inside the dipole gap is further enhanced [4,6].

Permanent magnet has a disadvantage of poor temperature dependence. This disadvantage can be approached from an opposite direction. Indeed, it was found that decreasing a temperature of the magnet has a great advantage in increasing the magnetization strength. Appreciable amount of an increase of field strength was observed. PM can be used for cyclotron or FFAG (Fixed Field Alternating Gradient) accelerator for accelerating charged particle.

Application of our high field permanent magnet can be extended to a variable field hybrid magnet with a combination of electro-magnet or superconducting magnet in a field level of 3 Tesla. This magnet may open to a possibility of 3 Tesla synchrotrons.

An application to a PM solenoid field is also attractive where charged particle is focused effectively. [7,8]

### 2 HIGH FIELD PERMANENT MAGNET

In most permanent magnet combined with iron pole and yoke, the field strength is several kG even when one uses strong NEOMAX whose  $B_r$  is 1.2 Tesla. This is because the magnetic field strength  $B_g$  in a dipole gap is expressed as,

$$B_g = \frac{l_m}{d+l_m} \mu_0 H_c \approx \frac{l_m}{d+l_m} B_r \quad (1)$$

where  $H_c$  is coercive field strength of the PM material,  $B_r$  is its residual field strength,  $l_m$  is a magnet length and  $d$  is the gap length. The eq.(1) is plotted in Figure 1.

See Figure 2 for this dipole magnet configuration. In most of the configuration of the magnetic circuit, iron pole and iron yoke is designed so that they are not at a saturated level. Relative permeability of the iron is high and presence of iron can be neglected to the contribution of the gap field strength and does not appear in the eq. (1).

For a small  $l_m/d$  ratio, field strength of the gap is proportional to it and become a fraction of  $B_r$ . Thus it is common that the maximum field strength is less than half of  $B_r$  in this conventional configuration. The field strength of the gap does not exceed  $B_r$  even at the limit of large  $l_m/d$  ratio. When the permanent magnet is placed alone without iron, the gap length is nearly equal or less than the magnet length and again, the field strength are half or less than  $B_r$ .

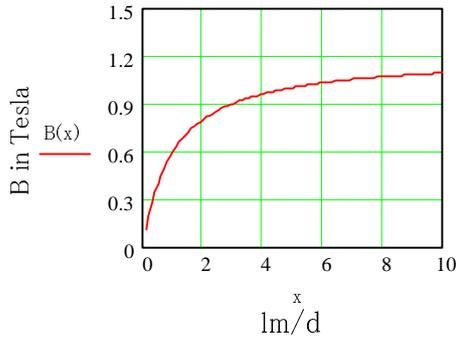


Figure 1. Gap field strength vs. magnet length to gap ratio

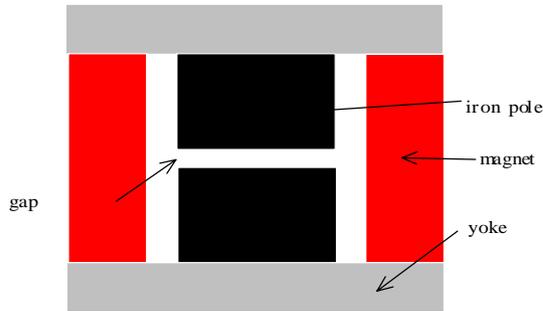


Figure 2. Cross section of an ordinary permanent magnet

K. Halbach invented an ingenious magnetic circuit [5]. In his configuration, pieces of REC (Rare Earth Cobalt) magnet material are placed on a ring where a direction of magnetization is rotated locally in a way so that resultant field forms a specified multipole field. This magnetic circuit is shown in Figure 3. The original circuit was a single layer and iron pole or yoke are not used. For a dipole, he derived a simple formula for a gap field strength  $B_g$ ,

$$B_g = B_r \ln\left(\frac{r_2}{r_1}\right) \quad (2)$$

where  $r_1$  and  $r_2$  is an inner and outer radius of the magnet. This equation is quite challenging, as there is no theoretical upper limit. In fact there is a limit as shall be explained later. To realize a high field as much as possible we started from this Halbach magnetic circuit. Permeability of the REC or NEOMAX or ferrite material is all about 1.05, close to unity. Superposition of magnetic field holds approximately. The field source located at long distance can contribute to the field at the centre accumulatively which is expressed as a logarithm of the ratio of the outer and inner radius. Efficiency is poor from outer location. The efficiency is even worse for a Halbach

Quadrupole where logarithm is replaced by  $2\left(1 - \frac{r_1}{r_2}\right)$ .

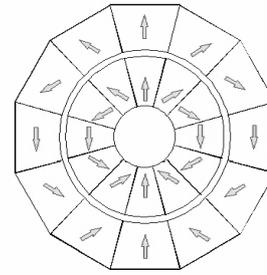


Figure 3. Cross-section of Halbach type dipole magnet. Red arrows show a direction of magnetization

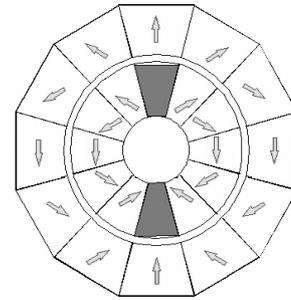


Figure 4. Cross-section of Extended Halbach dipole magnet. Blue colour indicates saturated iron.

To improve the efficiency, we introduced an iron pole to the Halbach REC configuration as in Figure 4. REC is replaced to NEOMAX. The field strength of this Extended Halbach magnet can be written approximately as,

$$B_g \approx \frac{B_r l_m + \frac{l_i}{\mu^*} B_{s0}}{d + \frac{l_i}{\mu^*} \frac{S_g}{S_i} + l_m \frac{S_g}{S_m}} \quad (3)$$

Parameters  $S_m$ ,  $S_g$ ,  $S_i$  is respectively cross sections of permanent magnet, gap, and iron.  $B_{s0}$  is a saturated induction of the iron pole and  $\mu^*$  is a relative permeability of the iron. Eq. (3) indicates the saturated iron pole is effective to increase the field strength. A saturated permeability of the iron approaches unity. Note the saturated induction of the iron  $B_{s0}$  is greater than the residual field of the strongest permanent magnet material NEOMAX [6].

The iron pole can be designed so that it is partly not saturated and the other part is partly saturated. This strategy contrasts to a conventional design principle. Here iron pole is intentionally driven into saturation. It is also possible in our case, to use the iron pole as a flux compressor where iron is not fully saturated. This effect is expressed as a ratio of cross section of the gap to PM and iron which is shown in the second and third term in the denominator.

At higher field level, we should take into account a demagnetisation effect of the PM material. This was not considered either in eqs. (2) or eq. (3). Under a strong external magnetic field the magnetization strength is reduced. In either Halbach or Extended Halbach type of high field configuration, the outer part of the magnet produces strong magnetic field on the inner part of the magnet. This problem could be coped with by selecting the material of high coercivity. In a 4 Tesla model magnet, we have used two different kinds of materials, namely material of high  $B_r$  and high  $H_c$  [4].

### 3 MODEL 4 TESLA DIPOLE MAGNET

In order to convince ourselves that Extended Halbach scheme should work, a scaled down model magnet was designed and constructed. Choice of inner radius of 3 mm and outer radius of 100 mm of 1.2 Tesla NEOMAX should generate 4.2 Tesla dipole field. The length is 150 mm. By simple scaling, inner diameter of 30mm, the outer diameter must be 1 meter for this field level. This size could be greatly reduced if the magnet is operated in liquid nitrogen temperature. For the assembly of the strong magnetic material, special tools are prepared. Pieces of arc shaped MEOMAX material was inserted by using the prepared tool manually. The assembly was very difficult resulting in an unacceptable level of mechanical tolerance. Sharp tip of the magnet material was fragile and easily came off. In future construction of the magnet, we are planning each size and shape of each piece of magnet materials should be minimum number of standard size and minimum number of magnetization directions. This might be inevitable to construct actual full-scale magnet as well as reducing the cost of the magnet.

The maximum field strength in the gap was 3.9 Tesla although the designed strength was exceeding 4 Tesla. The reason of this discrepancy may be a reduction in magnetization of the material. This is left to a further study in future. To increase the field strength further, the magnet is cooled down to  $-40$  degrees C. The field gain was about 0.5 Tesla. In Figure 5, a temperature dependence of the material is plotted.

The assembled magnet is shown in Figure 6 with a display of Hall sensor showing 4 Tesla was achieved during magnet measurement. The field distribution was measured with a small size of 1 mm Hall sensor. Preliminary result showed a considerable amount of field inhomogeneity. This was corrected by a shim inside the magnet gap. After the shim, field deviation from the designed distribution became 0.4 %. Further improvement should be done for the application of the accelerator. Magnetic field measurement system is also underway at Magnetic Sensor Laboratory at Lviv as a collaboration program. The system incorporate several number of micro sensor tips together and field distribution can be scanned in a short time of period.

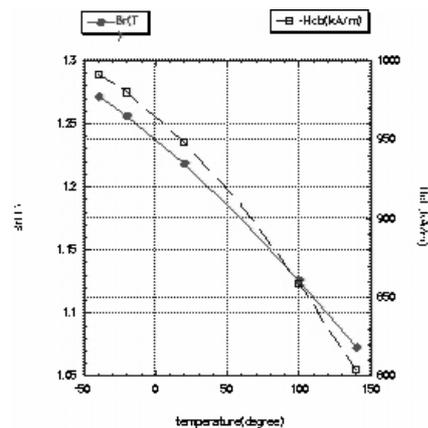


Figure 5. Temperature dependence of  $B_r$ .

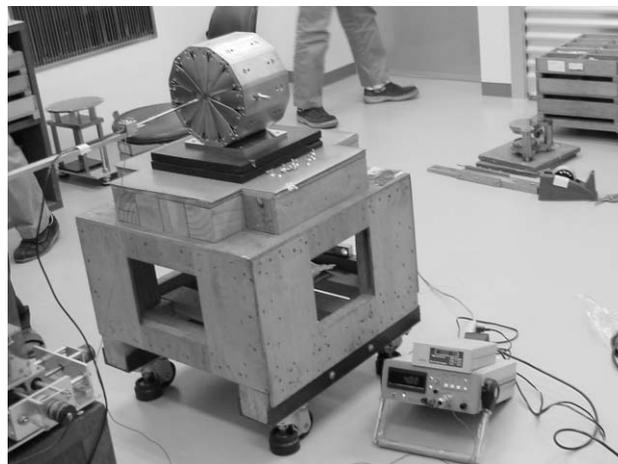


Figure 6. Assembled 4 Tesla permanent magnet and a measuring device.

### 4 ACKNOWLEDGEMENT

We would like to thank Drs. Soga, Yamada, Takada, Noda, Kanazawa and members of accelerator physics and engineering division in NIRS for continuous encouragement of this work.

### 5 REFERENCES

- [1] G. Jackson, FERMILAB- TM-1991
- [2] M. Kumada et al., Proc. 9<sup>th</sup> conf. on Magnet technology, Zurich, p.142 (1985)
- [3] N. Nakamura et al report, ISSN 0082-4798, Ser. A No.3378, April 1998, University of Tokyo
- [4] M. Kumada et al., patent pending.
- [5] K. Halbach, IEEE Tran. NS-26(1979), 3882.
- [6] K. Halbach, NIM, 169(1980)1, K. Halbach, NIM, 187(1981), 109, K. Halbach, NIM, 198(1982)213.
- [7] M. Kumada et al, PAC01, Chicago, 2001
- [8] Y. Iwashita, PAC93, Washington, D.C., 1993. p.3154.
- [9] T. Fujisawa et al., NIM B, 124(1997)120-127